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NASA

Analysis of Supersonic Flows using k-ε Model and the RPLUS code; Progress towards High Speed Combustor Analysis.

by J. Lee

Sverdrup Technology Inc./CFD Branch

for Workshop on Computational Turbulence Modeling

Sept. 1993

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Outline

- Problem of Interest - High Speed Combustor Flow Fields
  - Parameters need to be Resolved
  - Key Problems of Interest
- k-ε Model and RPLUS code
  - Numerical Technique
  - Models being Tested
  - Some Results
- Summary

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Problem of Interest

- Analysis of Chemically Reacting flow inside of Supersonic RAM jet Combustors-Two Key Parameters need to be determined.
  - Mixing/Combustion Efficiency
  - Kinetic Energy Efficiency (Flow Losses)
  - Inlet, Diffuser, etc..
- In order to do get some ideas on those parameter following (Potential Loss Mechanisms) must be modeled/determined correctly.
  - Mixing, Shear,
  - Turbulence, Vorticity,
  - Shock-waves, Heat Transfer,
  - Fuel Injector Drag, Poor Wall Pressure Integral,
  - Chemical Dissociation.

from 2nd JANNAF workshop on SCRAMjet Combustor performance workshop

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Mixing and Injector Design

- At High Mach Number($M \sim 5.0$ +).
  - Doesn't mix well!
  - The Natural diffusion mechanism very INEFFECTIVE.
  - Fuel Residence Time Extremely Small- Even with Fast Fuel Such as H_2
- Geometrical Complexities
  - To induce Favorable mixing and Flame holding features
    - Back-Step/Stream Wise Vorticity/Shock-Wave Interactions
  - Unsteady Mechanism also being Envisioned as mixing enhancement
    - Kumar, Bushnell and Hussani(1987)

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Introduction of Externally Generated Mixing Enhancements

- Some External helping hand needed => Modeling Difficulties.
- Externally Generated Vorticity Through Sweep angle of the Ramp injector.
  - Davis(1990), Riggins and McClinton(1990), Drummond(1991).
- Multiple Transverse Injection.
  - Hartfield et. al. (1991)
- Flame holding tricks/ Back-step with Recirculation.
  - Hartfield et. al.(1991)
- Simplified analysis of these features very difficult because of limited database/understanding (Attempts are being made using CFD solutions- JANNAF Combustor Subcommittee).

Numerical Modeling(CFD) of Combustor Flow Field

- CFD Analysis.
- Numerical Modeling=> Overall Analysis of performance => Difficult
- Overall Laminar Flow Fields with Complex Geometry/Finite Rate Chemistry has been demonstrated.
- Finite Rate Chemistry Model- Yoon and Shuen(1989)
- Multiple Grid Blocks- Moon (1991)
- Analysis of a typical Injector Configuration with Zero Equation Turbulence Model using LU Scheme(RPLUS) code- Lee(1993)

Simple Zero Equation Turbulence model with multiple wall scaling Buleev-Inverse square rule can be used to extend model in to three-dimensional form. (Lee (1993))

- Good News/Bad News
- Typical velocity profiles can be reasonably predicted.
- Over all combustor flow features can be reasonably predicted.
- Near-wall temperature characteristics near non-equilibrium region around the injector and separated flow were poorly predicted.
- Overall spreading behavior of shear region poorly predicted.

- Two Equation Transport Turbulence Model has the potential to ease some of these difficulties.

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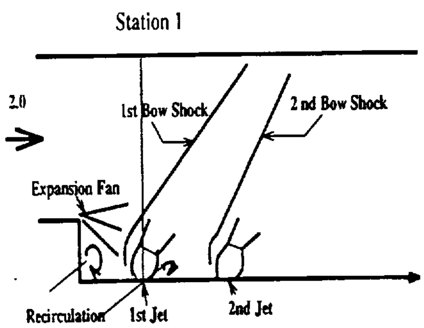

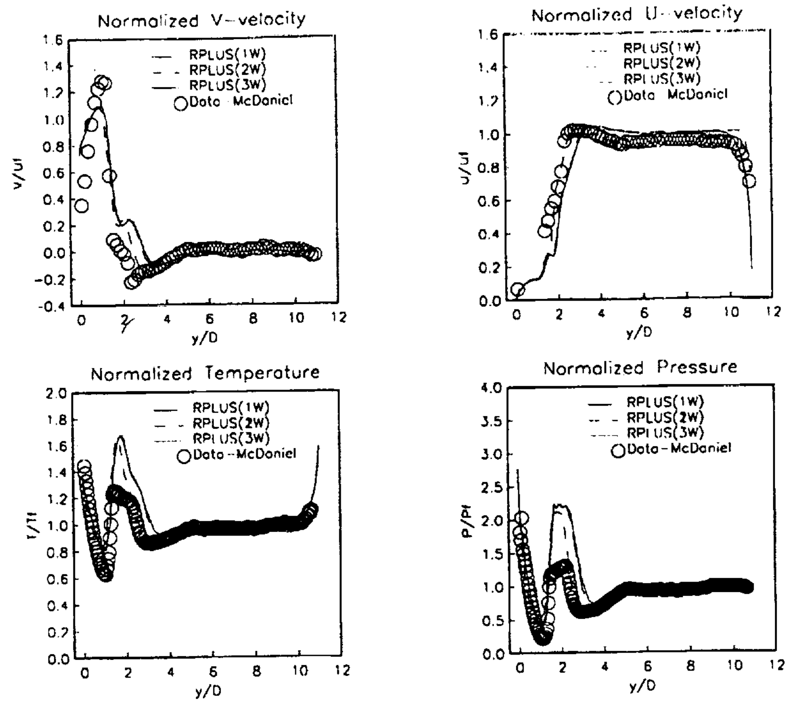

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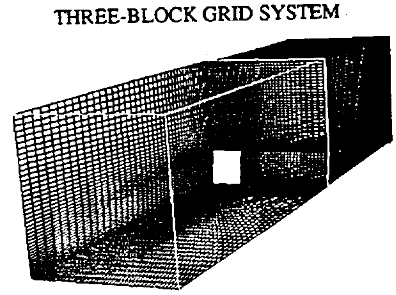
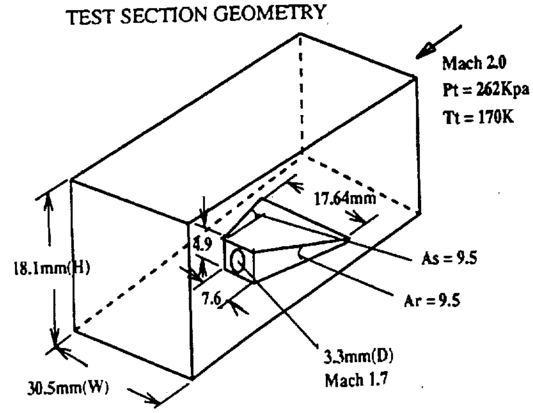
HARTFIELD ET. AL. (1990)

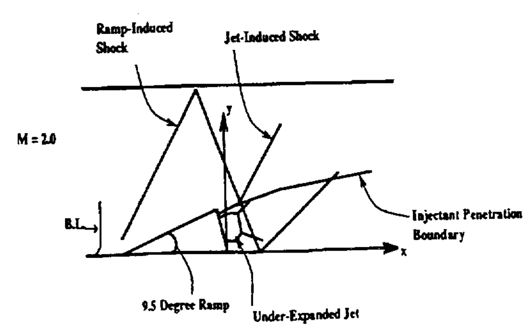
THREE-BLOCK GRID SYSTEM



TEST SECTION GEOMETRY



FLOW SCHEMATIC



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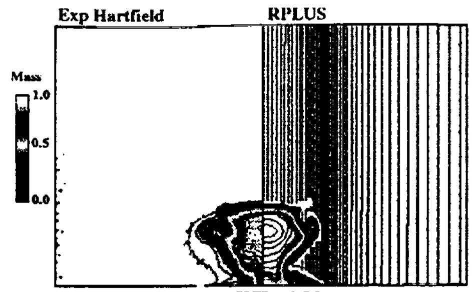
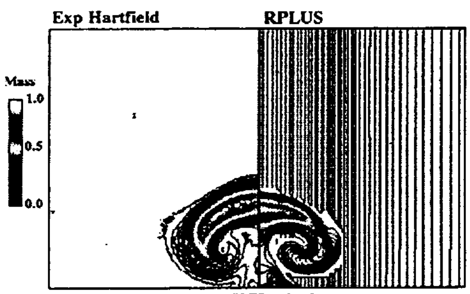
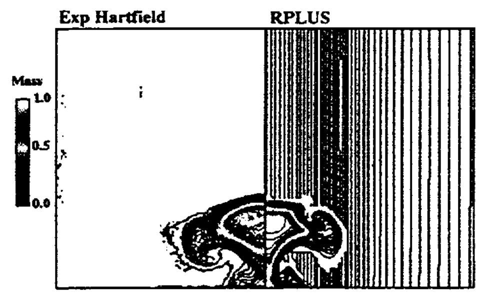


X/H = 1.06



X/H = 3.19



X/H = 2.13

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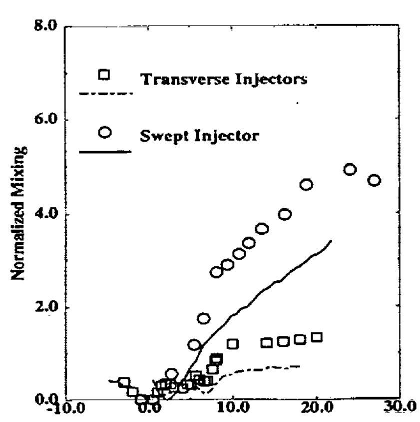
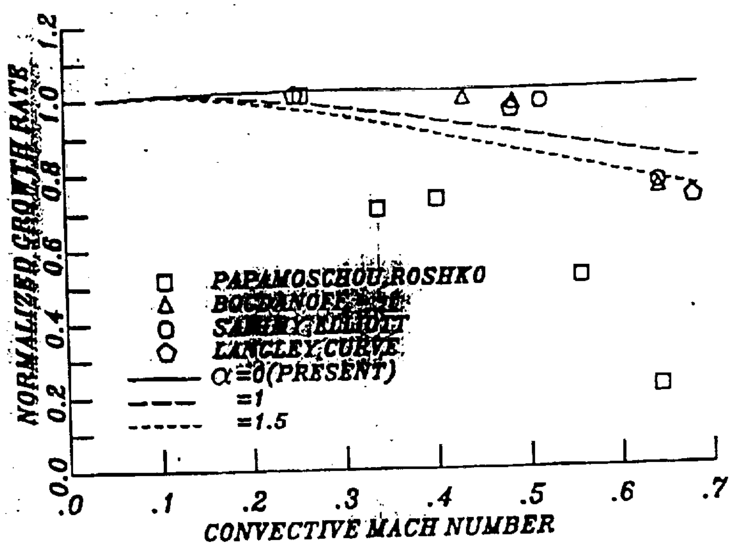
Mixing Efficiencies





GROWTH RATE VS. COMPRESSIBILITY EFFECT

DR. H. LAI

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Two Equations Transport Turbulence model are being Analyzed

- High speed turbulence models are some what Deficient (The deficiencies are well documented(Marvin(1986), Wilcox(1993)).

  Effect of Compressibility

  An-isotropy (Low/High Speed).

  Non-Equilibrium Flow Features (Low/High Speed).

  Near-Wall Flow(Low-Reynolds Number Features (Low/High Speed)).

  Inflexibility of handling Complex Geometry- Invariance Principle (Low/High Speed)

  Large Dependence in the Numerical Methods Used (especially elliptic Solvers).

  Appropriate Initial/Boundary Conditions

  Etc ...

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K-ε Model-RPLUS Development

- LU Based k-ε Model Solver-De-coupled Approach.
  - Mean-Turbulence Transport Equations
    - LU-SSOR- Yoon and Shuen- Explicit Terms Centrally Differenced
    - LU-SW -Steger and Warming- Explicit Terms Upwind Differenced
  - k-ε Models
    - Convective Terms + Diffusive Terms + Source Terms = 0.0
    - Model Only differ in Low-Reynolds Number Character.
    - Models performance are being Evaluated.
    - Implicit Source Term Handling Strategy also Being Studied

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k-ε Turbulence Models being studied for potential used in Three Dimensional RPLUS Code.

- Low-Reynolds Number Model plus Dilatational Terms
  - Chien (1976)
  - Launder-Shima(1976)
  - Shih(1990)
  - Various CMOTT derivatives of k-ε Model
    - Realizability
    - Invariance
    - Simplified Boundary-Conditions
- Performance of the Low-Reynolds number K-e model in low-Mach number flows have been demonstrated (Patel, Rodi and Scheuerer(1985), Steffen(1993), Launder(1992)).
- Some of the Potential Difficulties in high speed turbulence model are well documented (Marvin(1993), Coakley and Huang(1992).

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Evaluation and Development of the RPLUS/k-ε Model Solver

- Various 2D-3D problems are being studied to optimize the numerical method and to Evaluate model performance in supersonic flows in context to the LU based numerical Technique.
- Simple 2D k-ε models are also being used to study various components of the flowfield generated by the complex combustor geometry previously shown.
- Studying the Numerical method/Model Behavior/Model Performance.

  2D Supersonic Turbulent Boundary-Layer- Skin Fraction/Heat transfer (NASA Ames Database).

  2D Supersonic Shock-Wave Boundary-Layer Interaction- Skin fraction/Heat -Transfer/ Shock-wave(A. Smits (1990's))

  2D Shear-Layer - Mixing (H. Lai(1993))

  3D Fin/Flat Plate Interaction- 3D Corner Flows-Interaction Developed through a Fin generated Shock-Waves. (D. Davis(1992))

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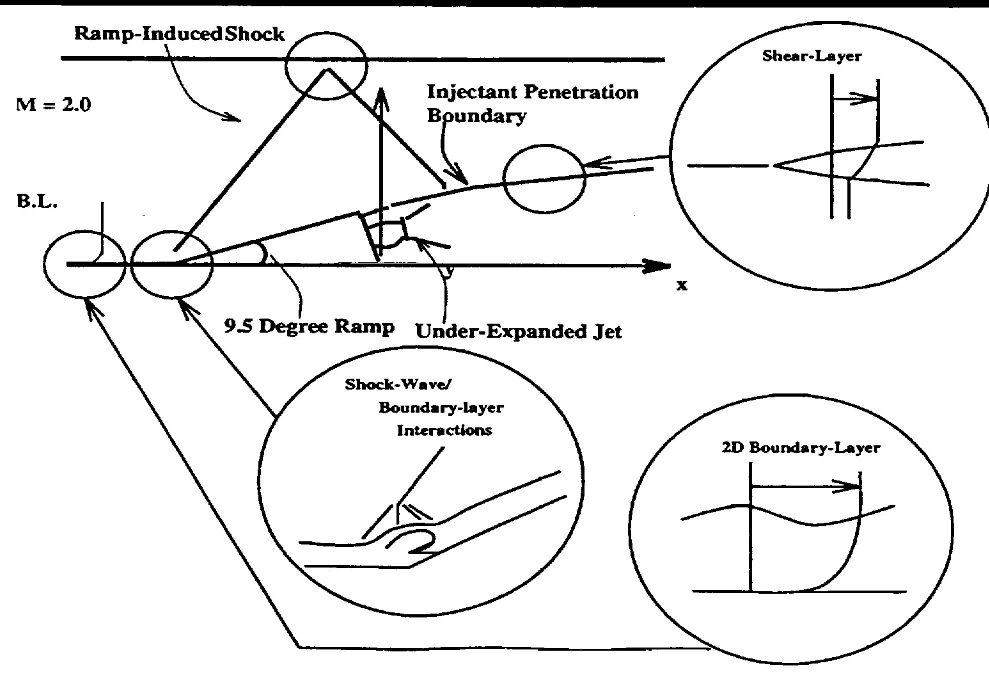

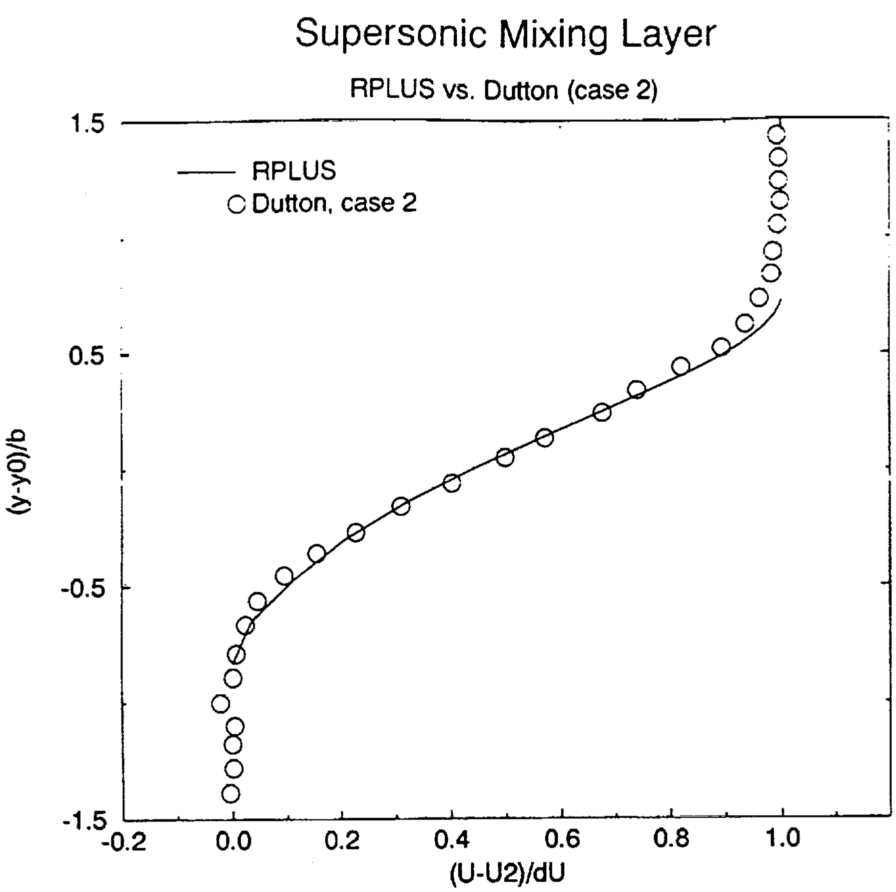

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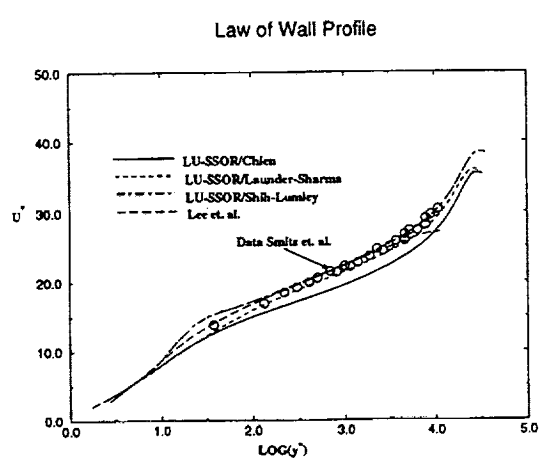
Boundary Layer

Mach 2.87

Re/m = 6.3×10^{7}/m



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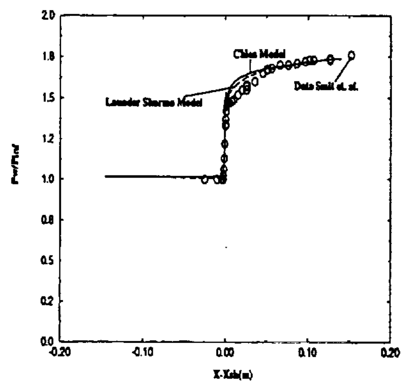
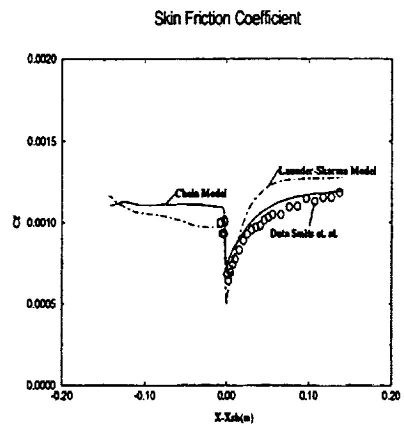
Turbulent Shock-Wave/Boundary Interactions
Mach 2.87
Ramp Angle = 8.0 degrees





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Other Factors

- Optimum Numerical Strategy with in LU frame work.
- Effects of Initial condition.
- Modeling of Compressibility terms/Dilatational terms.
- Modeling of Turbulent terms in the Finite Rate Chemistry Model. Anisotropy of Turbulence
- Effects Upstream and Down stream Influences (Inlet(K. Kapoor) and Diffuser(?)).
- Chemistry-Turbulence Model Interactions (A. Hsu-PDF).
- Numerical Robustness(A. Suresh).